

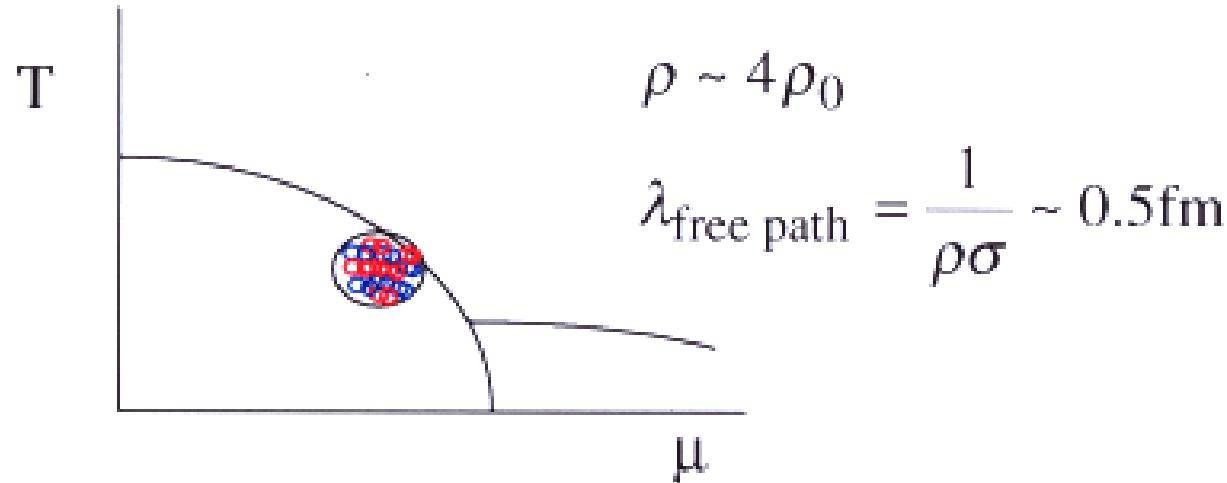
Review of Nuclear Reactions @ AGS

Craig Ogilvie, Iowa State University

- ◆ Properties of dense hadronic matter
 - review of pA and AA experimental results
- ◆ Link to SPS 40, 160 AGeV
- ◆ Future Opportunities
 - GSI, JHF upgrades, AGS in RHIC era

Physics Motivation For Dense Hadronic Matter (I)

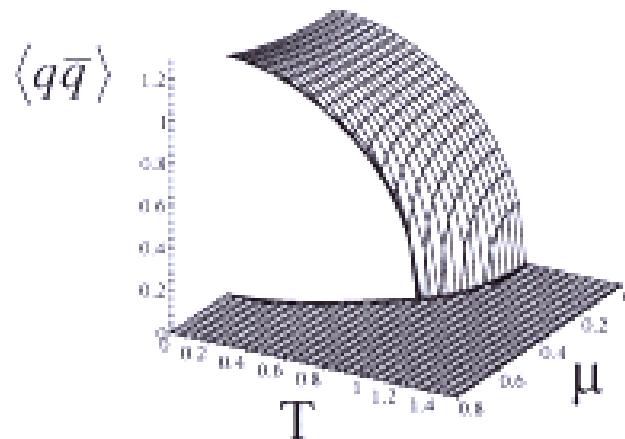
Consequences of Mean-Free Path of Hadrons



- ◆ Mean free-path very short, question independent 2-body collisions
 - n-body collisions or propagation off mass-shell hadrons
- ◆ Working ansatz
 - calculate collisions between pairs of hadrons
 - » propagation of resonances, formation and decay of strings
 - effects of dense medium incorporated in a mean field $U(\rho, p)$

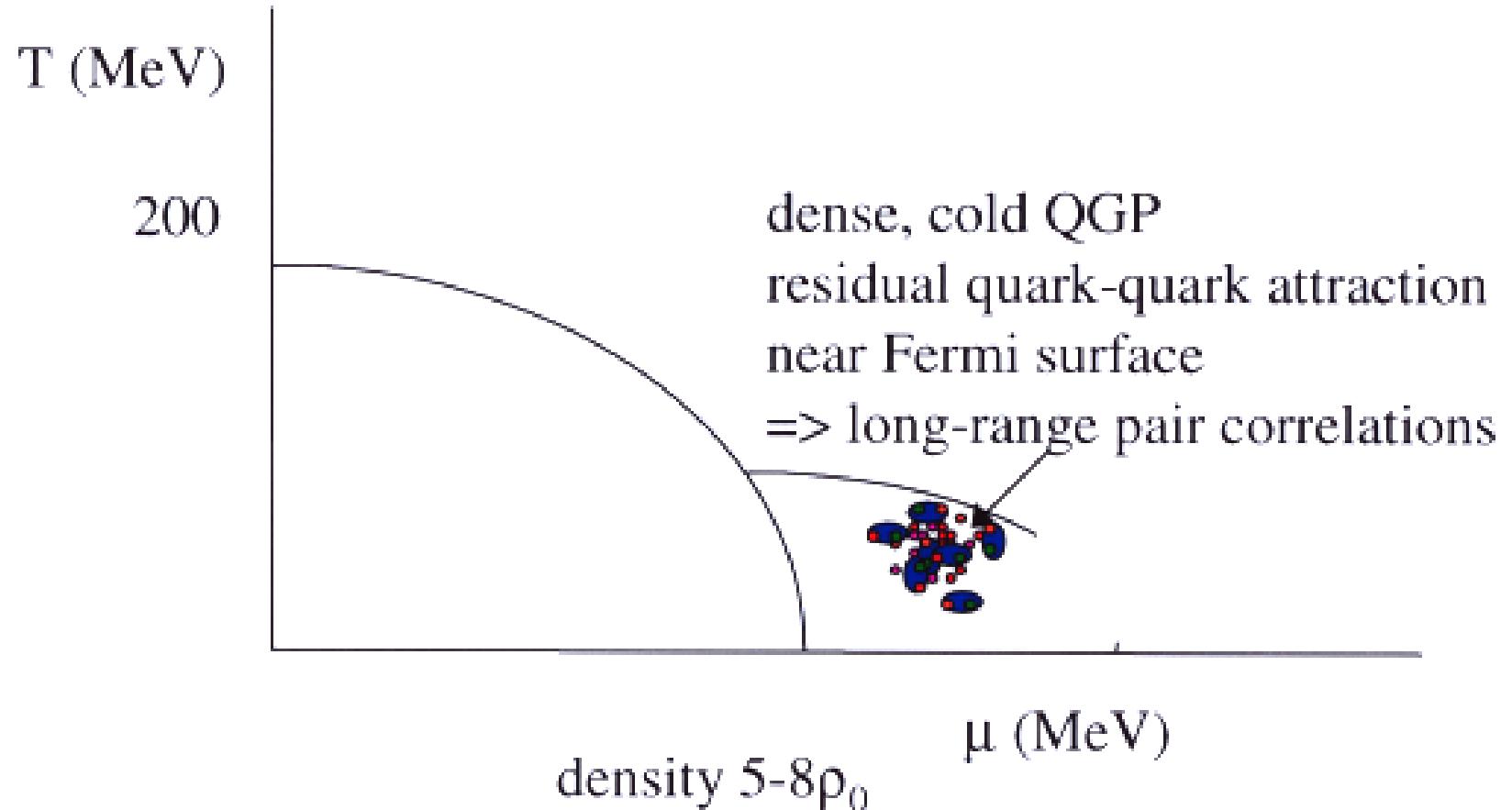
Physics Motivation (II): Possible Change of Hadron Properties

- ◆ Predicted change in $\langle q\bar{q} \rangle$ as function of T, μ
(Halasz et al. Phys. Rev. D 58, 096007 (1998))



- $\langle q\bar{q} \rangle$ predicted to go to zero at either high T or μ
- how rapidly $\langle q\bar{q} \rangle$ decreases varies between models
- ◆ Does this decrease in $\langle q\bar{q} \rangle$ happen and does it change the properties of hadrons ?

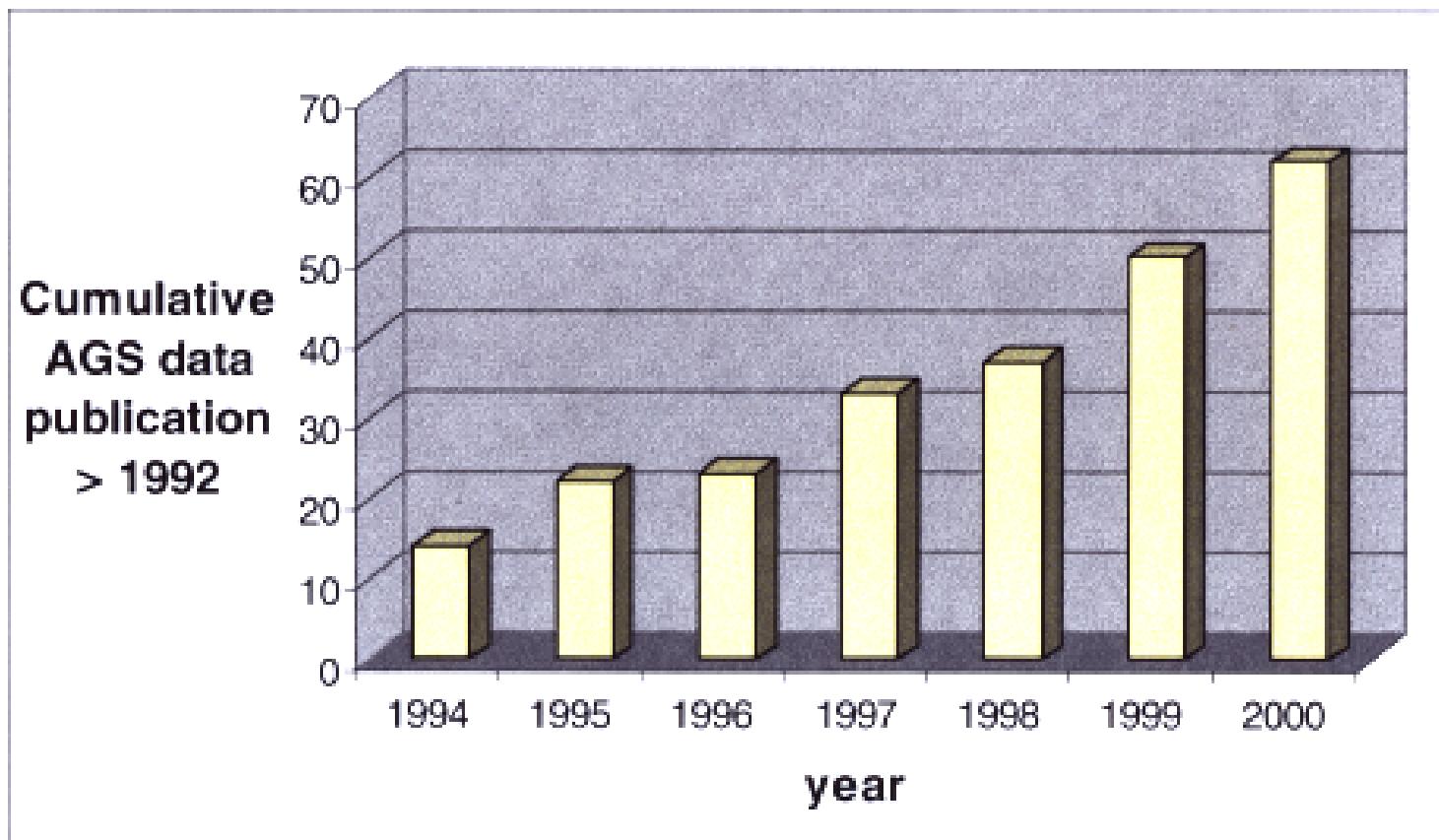
Physics Motivation (III): Color Superconducting Phase of High-Density QGP



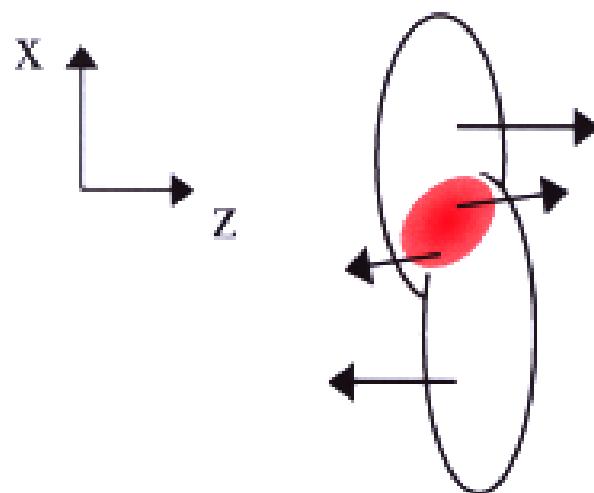
Talks by Krishna Rajagopal, Madappa Prakash

Data

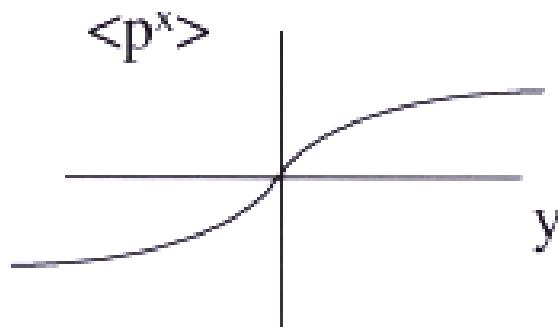
- ◆ p+A , Si+A, Au+Au
- ◆ 2 - 18 AGeV/c



Sideways Flow: Probe of Pressure Gradients in Collision Zone

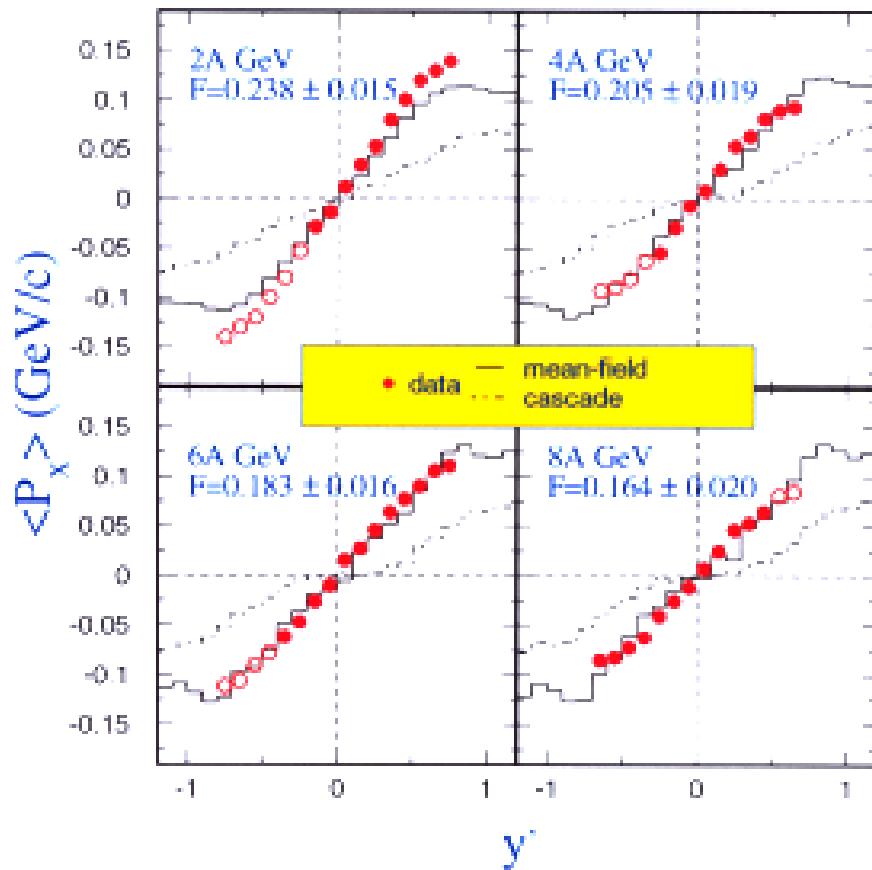


pressure gradients within reaction zone can cause deflection of baryons



$\langle p^x \rangle$ mean transverse momentum in reaction plane

Repulsion Driven by Gradients in Mean-Field

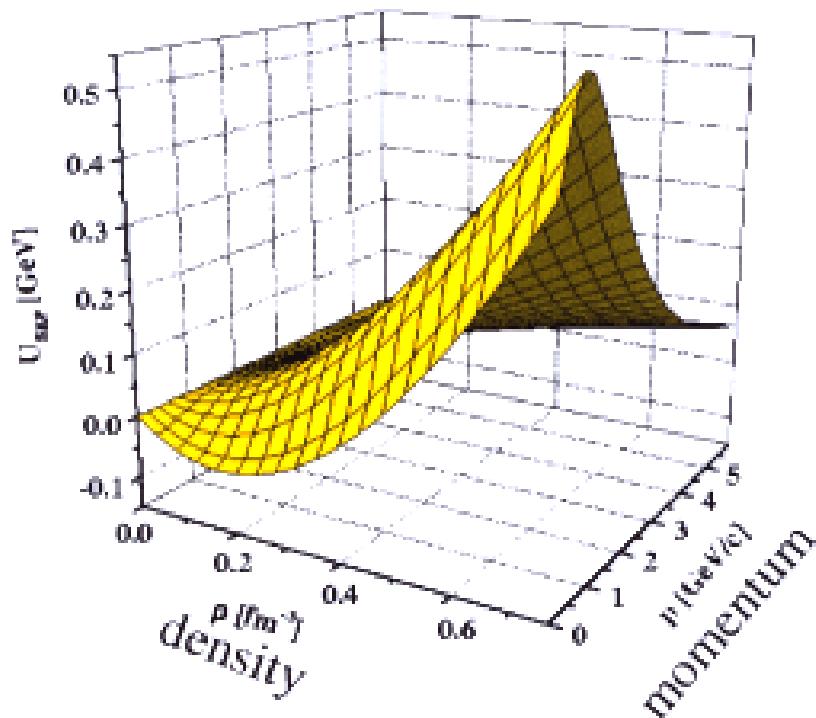


- Flow decreases as function of E_{beam}
- Measured sideways flow cannot be reproduced by cascade calculations (RQMD 2.3)
 - “thermal” pressure insufficient amount of deflection
- Additional repulsion caused by gradients in mean-field

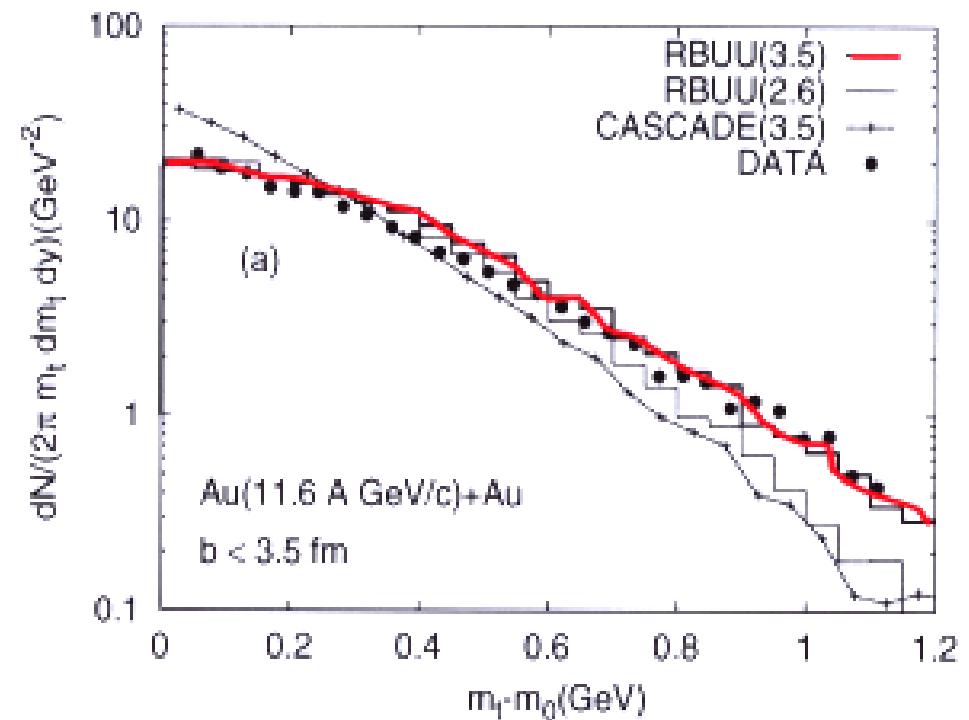
E895, Phys. Rev. Lett 84, 5488 (2000)

Mike Lisa E895 Talk

Predicted Mean-Field: Complicated ρ , p Dependence



W. Cassing et al.,
Nucl. Phys. A 674, 249 (2000)



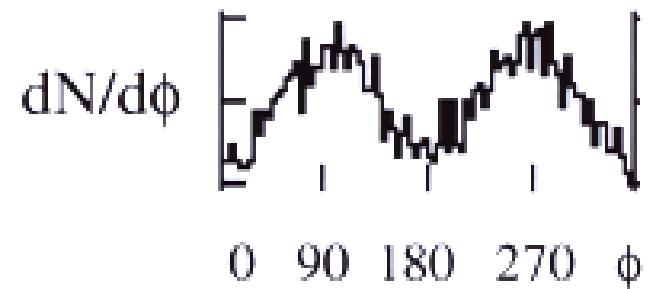
E866 Phys. Rev C
57, R466 (98)

P.K. Sahu et al.,
Nucl. Phys.A
672, 276 (2000)

- ◆ Momentum dependence of mean-field
 - successful in reproducing proton pt distribution

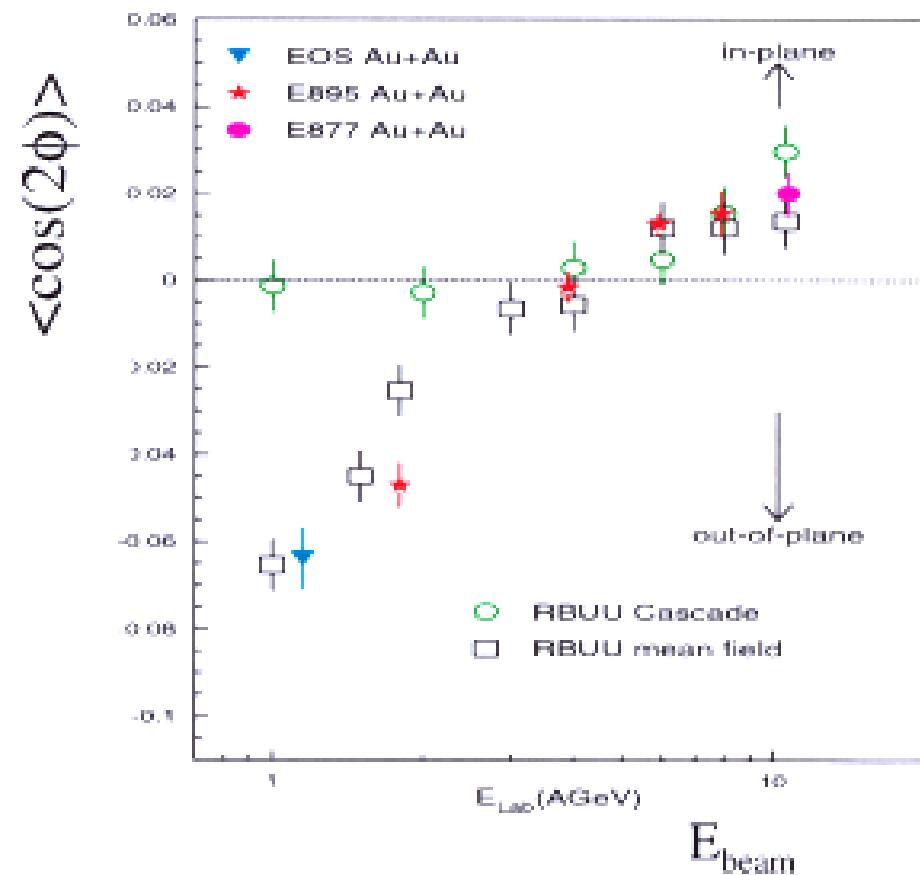
Proton Elliptic Flow vs E_{beam}

- ◆ At low E_{beam} azimuthal asymmetry oriented 90° to reaction plane
- ◆ High E_{beam} asymmetry oriented within reaction plane



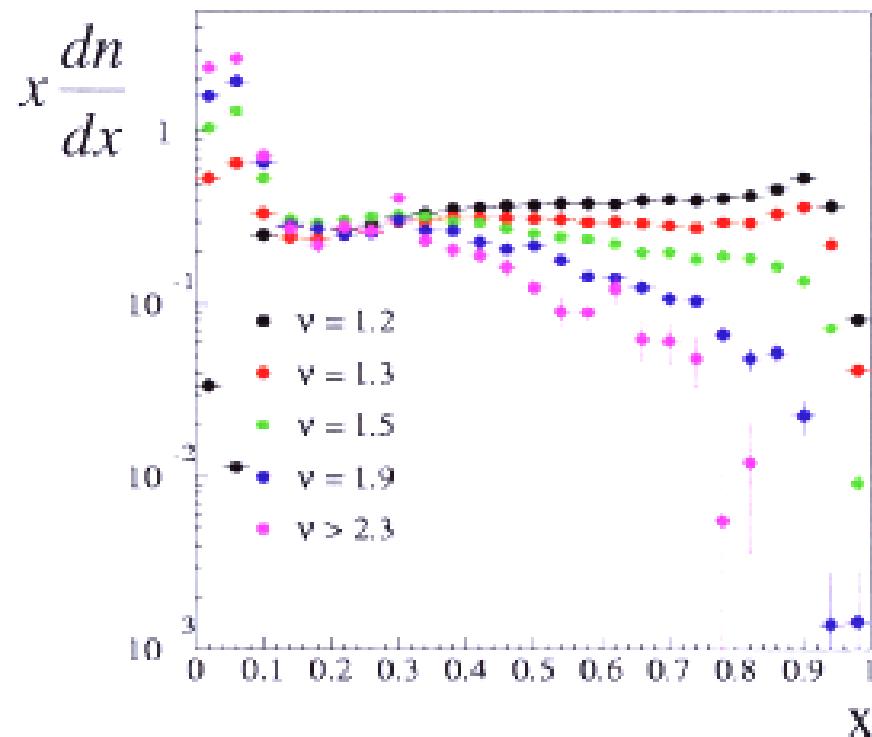
- ◆ Momentum dependent mean-field (\square) reproduces data

E895 Phys. Rev Lett 83, 1295 (1999)
P.K. Sahu et al., Nucl. Phys.A 672, 276 (2000)



Are Model Dependencies Under Control ?: pA Proton Distributions

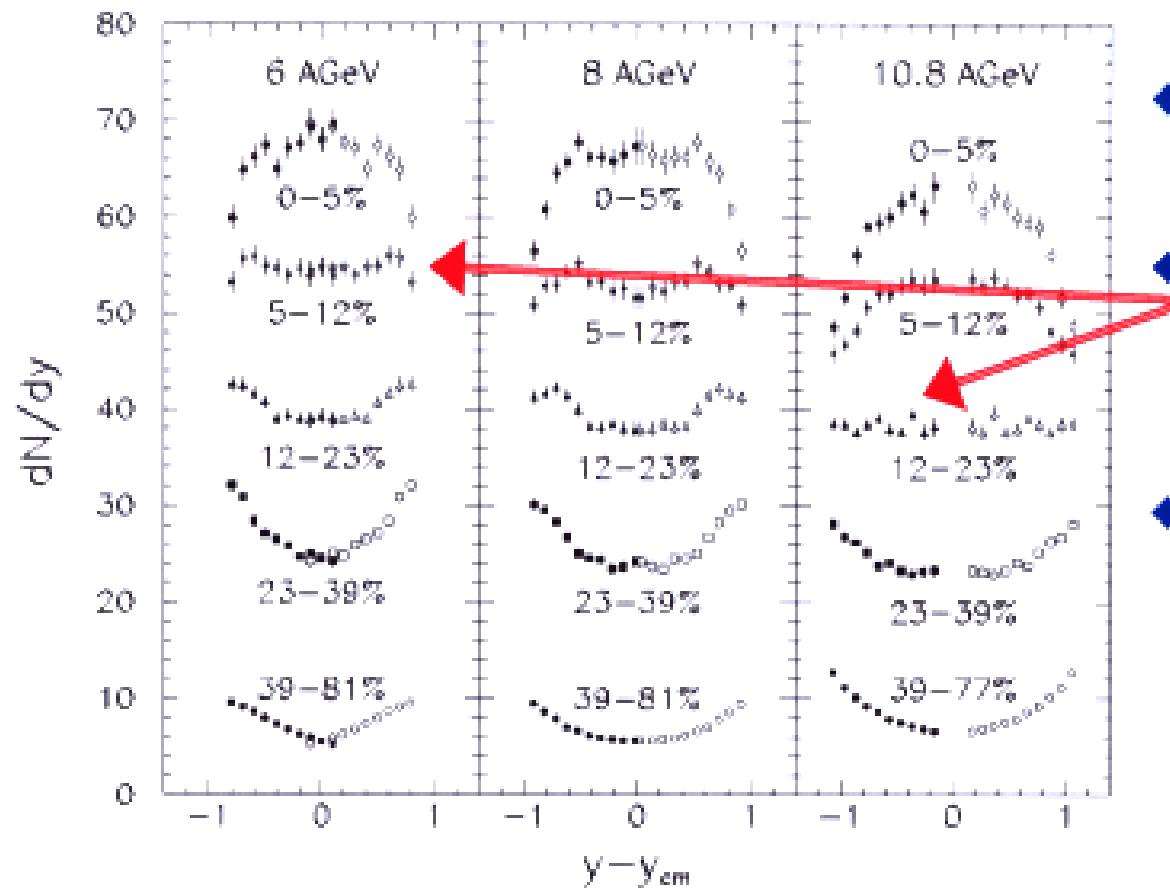
p + Be 12 GeV/c E910 preliminary



- ◆ $x = p/p_z$ beam
- ◆ Protons shift sharply backwards as number of collisions increase
- ◆ Confront microscopic dynamical models
 - baryon rapidity-loss $v \sim 1$
 - rescattering processes $v > 1$

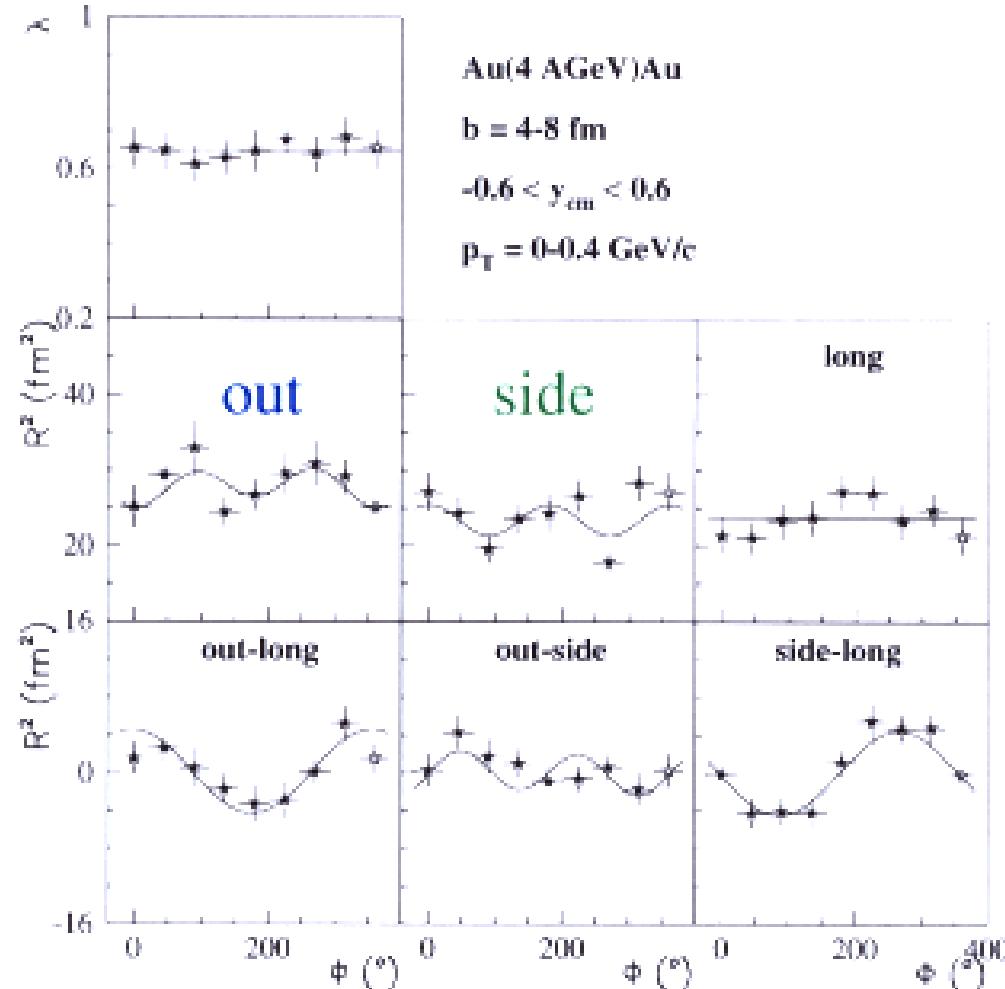
Brian Cole pA Talk

Critical Check II: Au+Au 6, 8, 10 AGeV



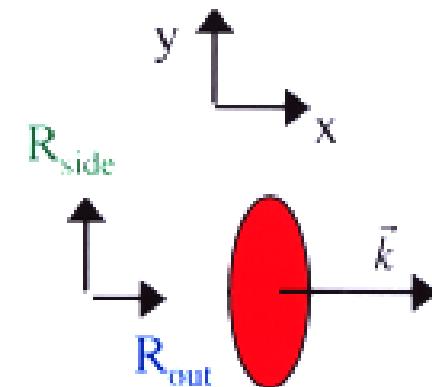
- ◆ Centrality dependence of proton distributions
- ◆ “Inversion” occurs in more peripheral reactions at higher E_{beam}
- ◆ Rapidity loss increases at higher E_{beam}

Critical Check III: Dynamics via Azimuthal HBT



E895, Phys.Lett.B496:1-8,2000

- Extracted HBT parameters vs reaction plane
e.g. when $\phi = 0$, $\vec{k} // \vec{b}$

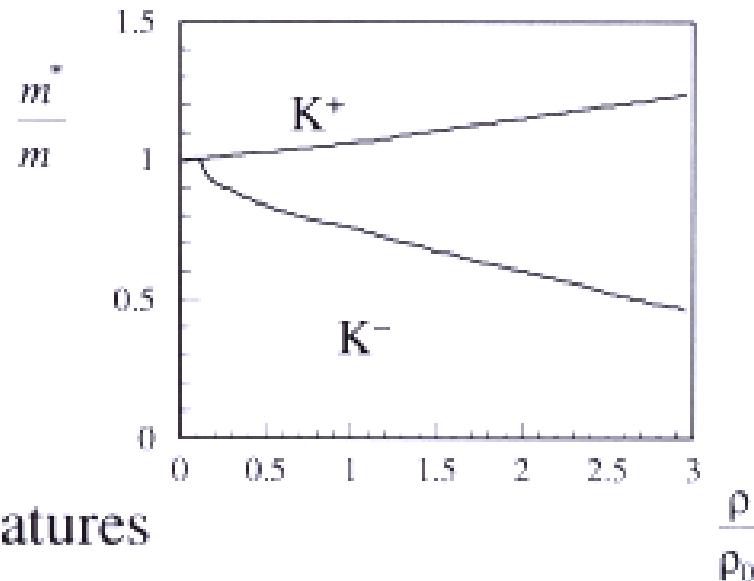


- $R_{\text{out}} < R_{\text{side}}$
initial overlap, expansion
=> “shape” @ freezeout

Mike Lisa E895 Talk

Do Produced Particles Experience a Mean-Field?

- ◆ K^- and \bar{K}^0 have attractive resonant interactions with baryons,
- ◆ For K^+ and K^0 the interaction is repulsive
- ◆ Model as either mean-field or effective mass

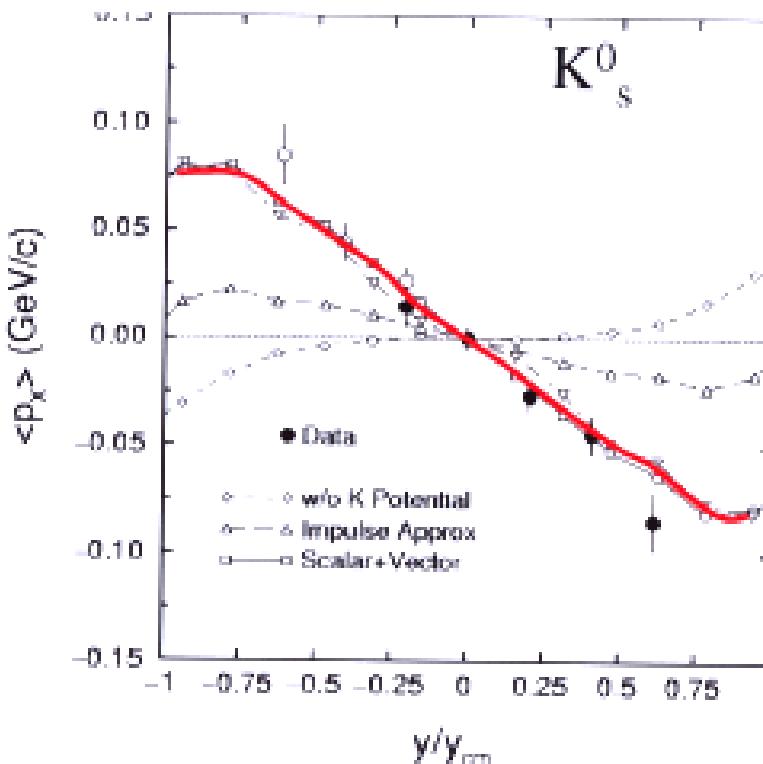
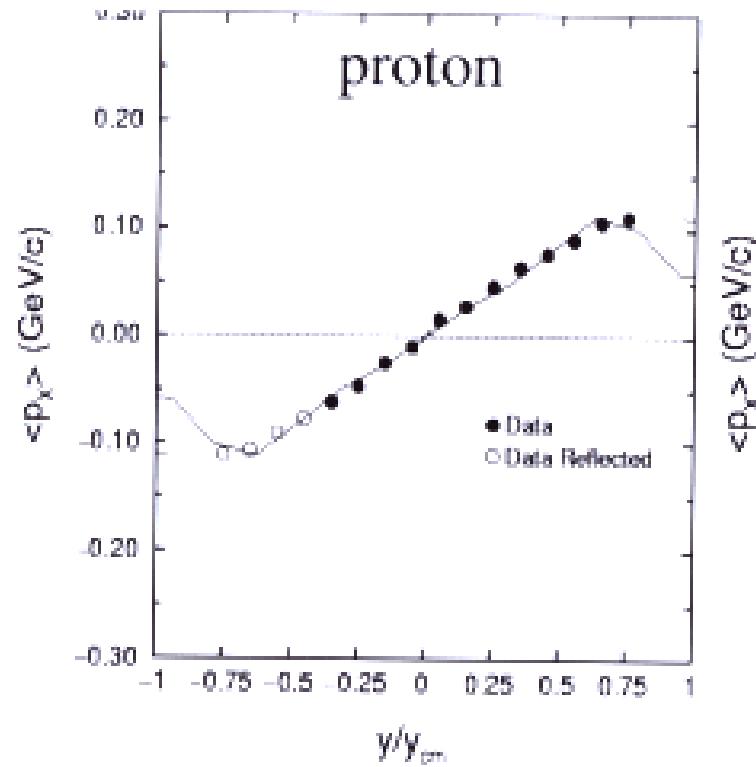


W. Weise
NPA610 35c, 96

Plotted at momentum = 0

- ◆ Signatures
 - increased $NN \Rightarrow K^- K^+$ phase space, increased K^- yield
 - » E917 Talk Burt Holzman
 - directed flow of K^+ , K^0 , repulsed from baryon flow

K_s^0 Anti-Flow Au+Au 6 AGeV



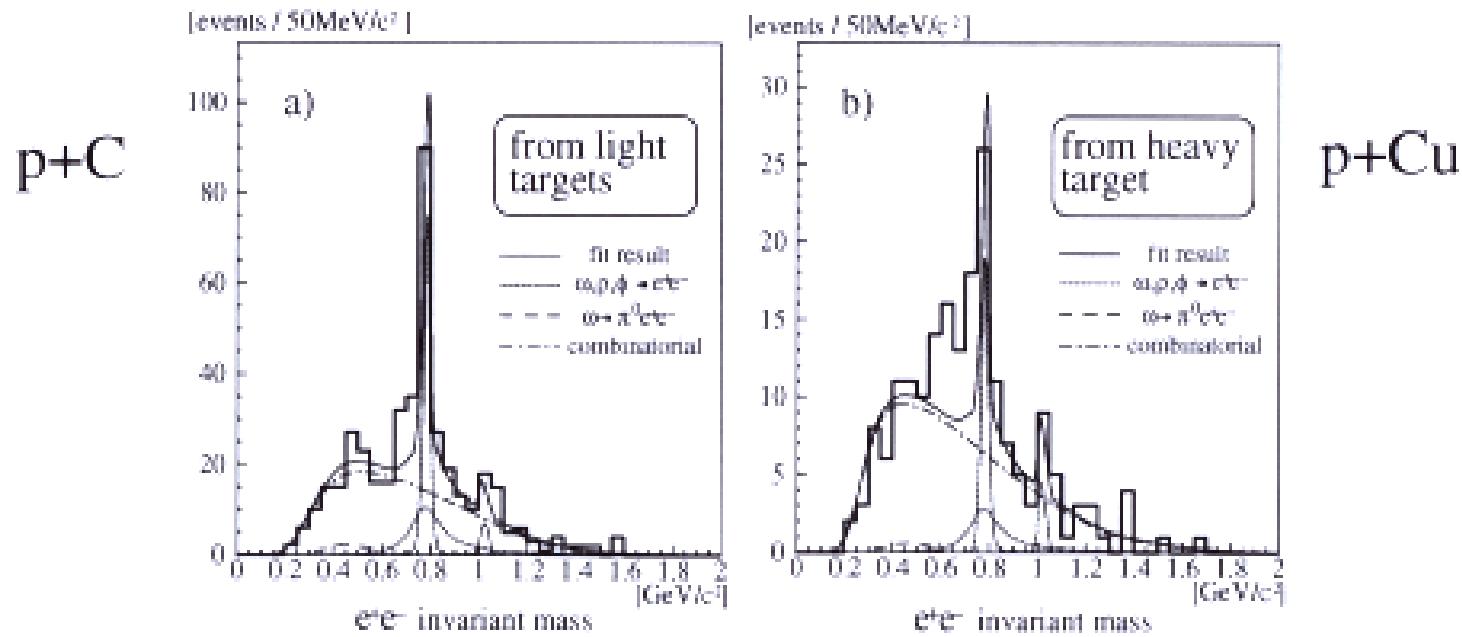
- ◆ Striking opposite flow for K_s^0
- ◆ Reproduced using repulsive mean-field for K^0 —

Chung et al.,
Phys. Rev Lett
85, 940 (2000)

Pal et al.,
Phys. Rev. C
62, 061903
(2000)

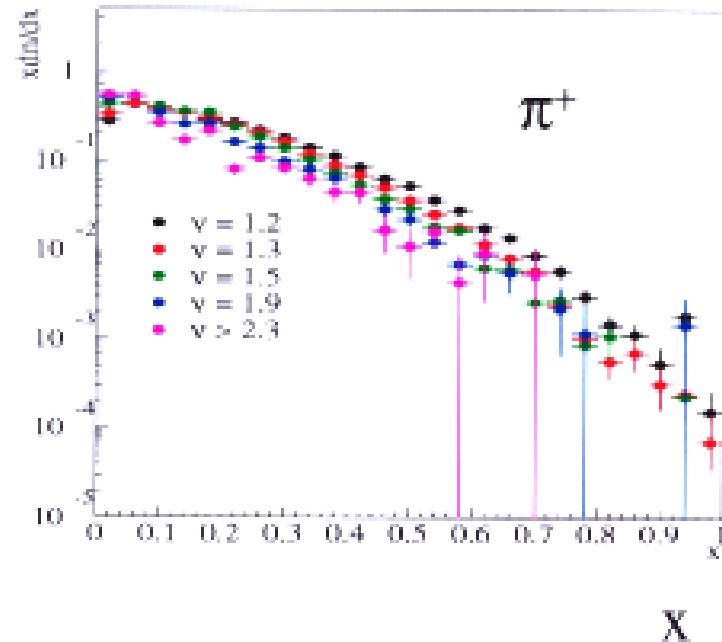
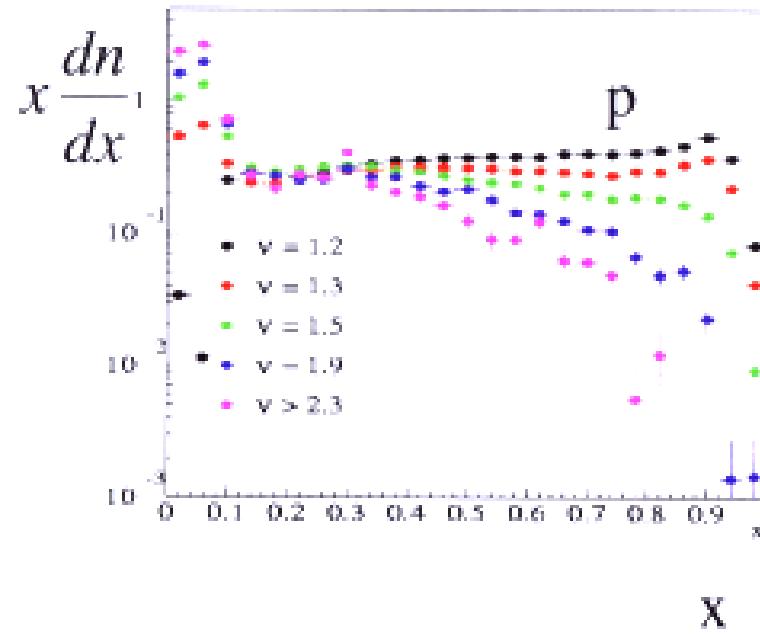
Hadron Properties In Medium

- ◆ No e^+e^- spectrometer at AGS
- ◆ Progress in measurements made at normal density
 - KEK 12 GeV/c pA $\Rightarrow e^+e^-$, K. Ozawa et al. nucl-ex/0011013



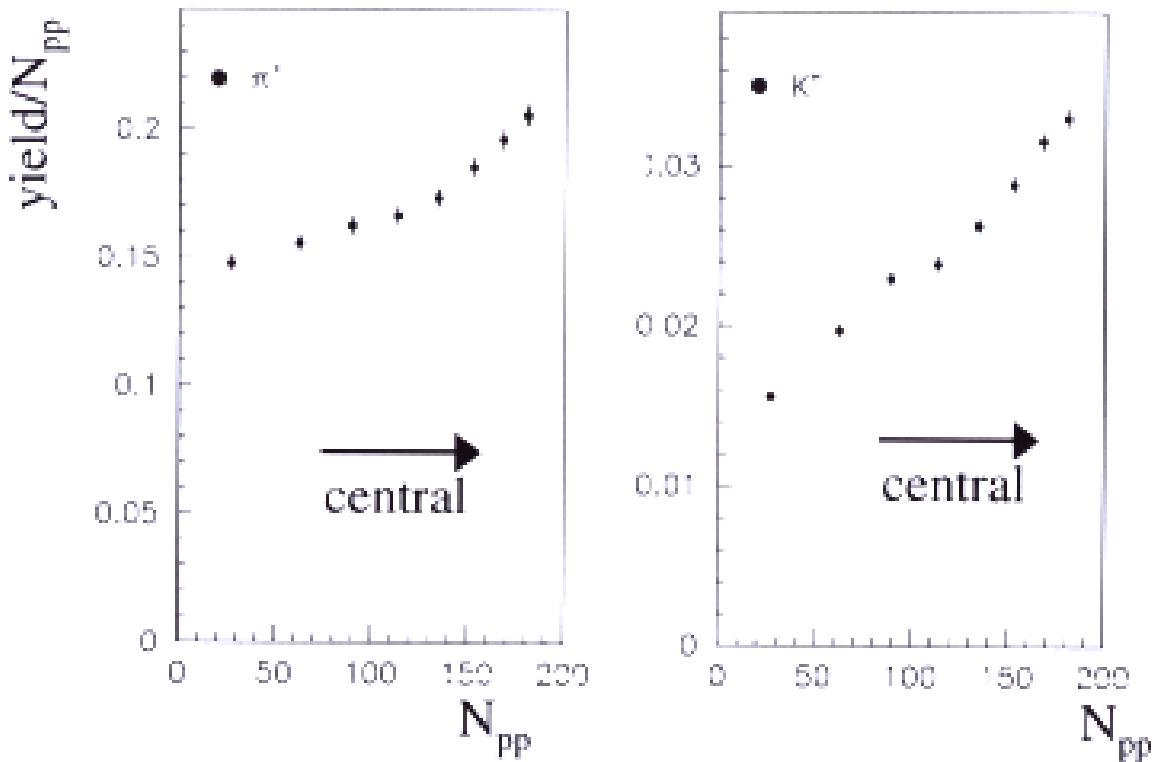
- ◆ 5-10 times more statistics to be presented by Kyoichiro Ozawa
- ◆ HADES pA, A+A 1-2 AGeV @ GSI program starting in 2001

Pion Production in pBe 12 GeV/c, $x = p_z/p_{\text{beam}}$



- ◆ Pions with significant fraction of incoming momentum, $x > 0.6$
 - often modeled as decay of quark-diquark, or recombination
 - collisions soften π^+ high x distribution, less than protons
- ◆ Dominant yield π^+ , $x < 0.3$, can be modeled as $p \Rightarrow \Delta \Rightarrow N + \pi^+$

Au+Au 10.7 AGeV K^+, π^+ Production vs Centrality



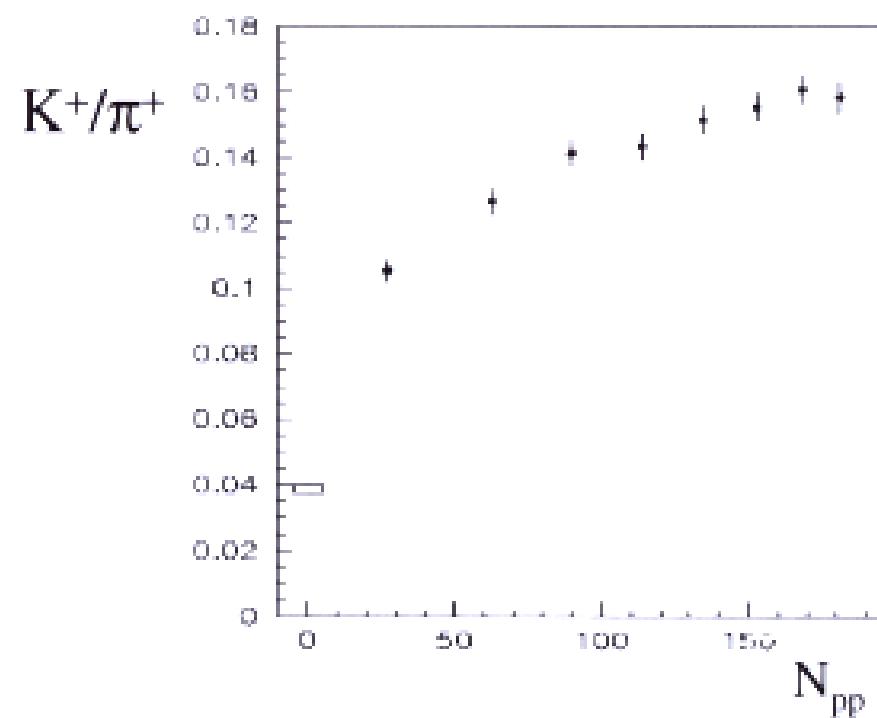
E866 Phys Rev C
59, 2173 (1999)

- ◆ Yields of (kaons, pions) / (number of participants)
 - increases from peripheral to central reactions
 - » consistent with multiple collisions per participant
 - K/π ratio increases with centrality

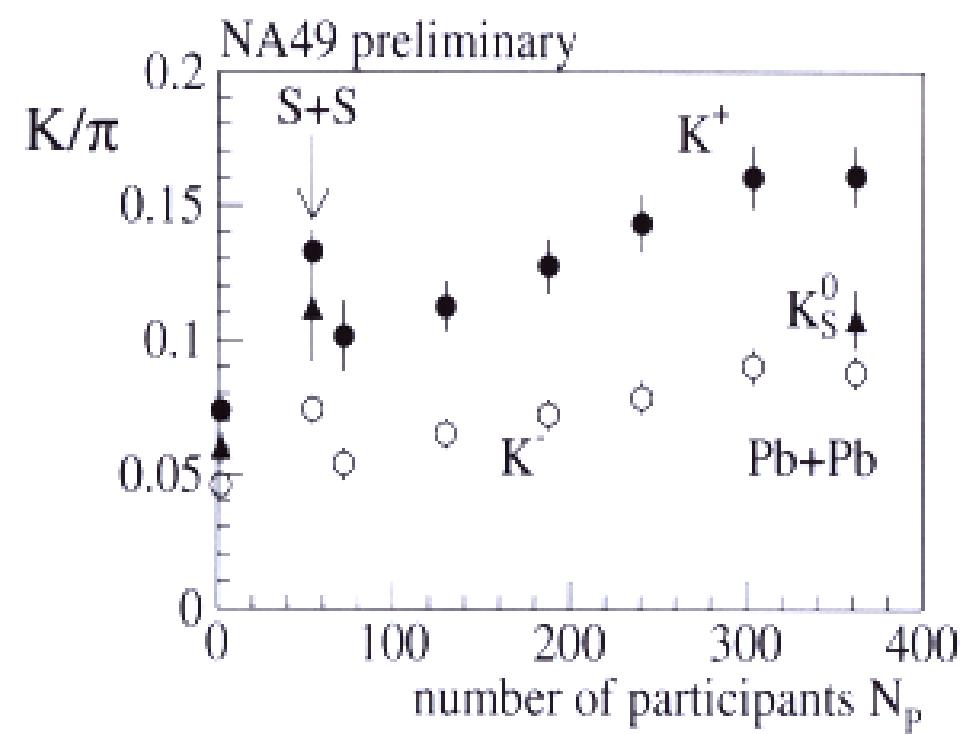
K/ π vs Centrality

Au+Au 10.7 AGeV

E866 Phys. Rev C59, 2173 (1999)

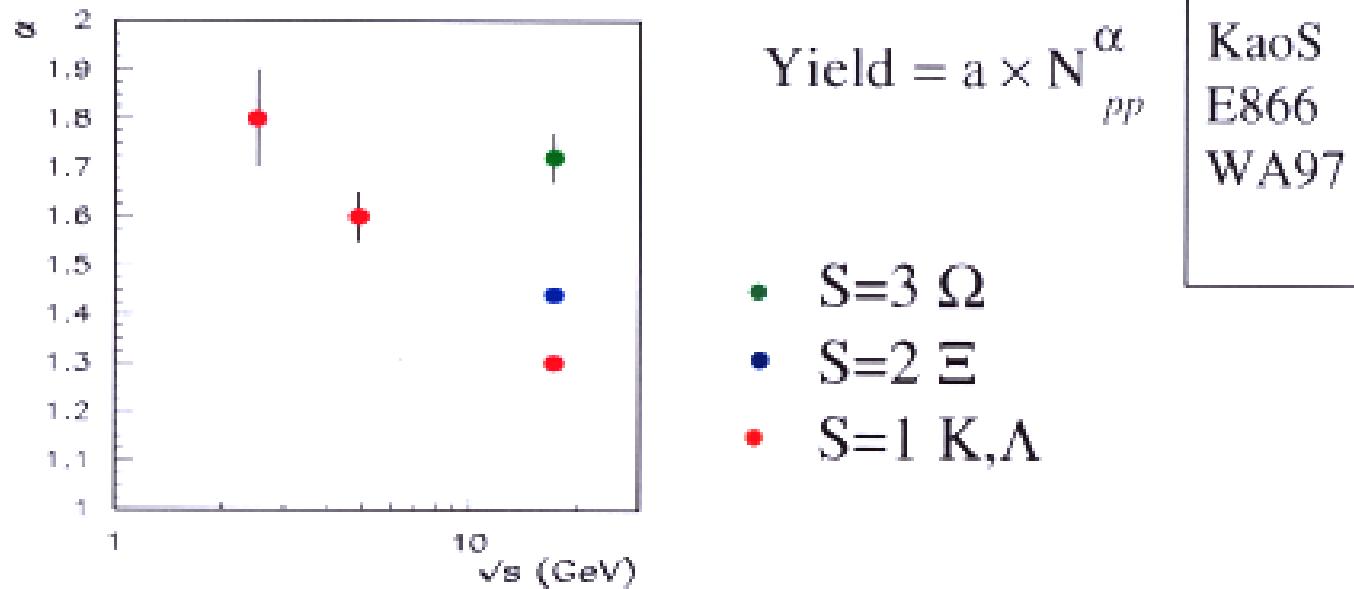


Pb+Pb 158 AGeV/c



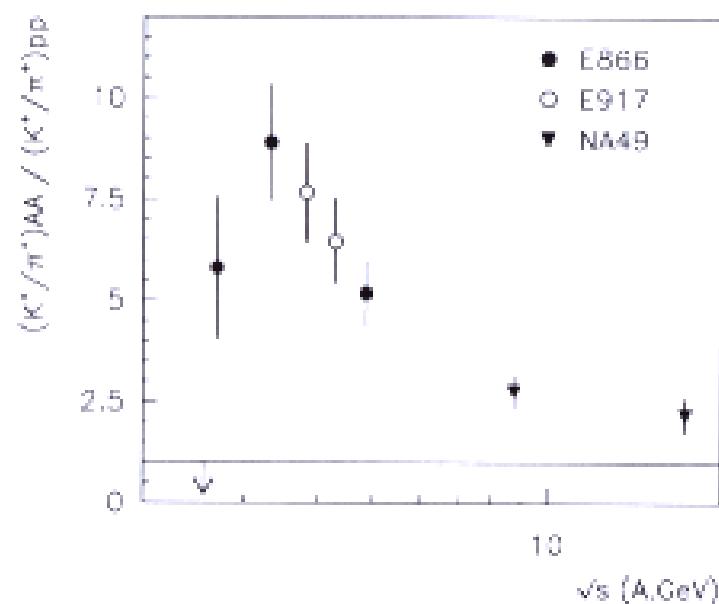
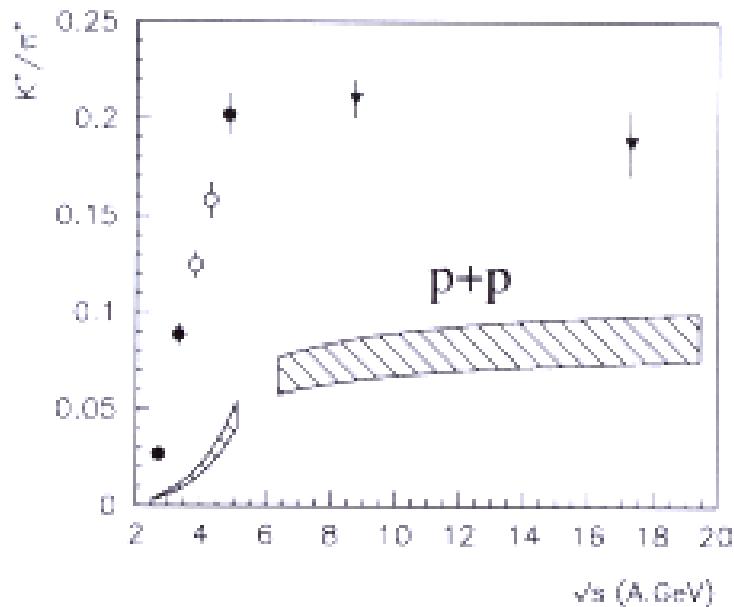
- ◆ K/ π increases from peripheral to central reactions
 - very similar behavior AGS and SPS

E_{beam} Dependence of Strangeness Enhancement



- ◆ Exponent, α , increases @ lower E_{beam}
 - secondary collisions relatively more important at lower E_{beam}
 - closer to K^+ threshold, each secondary collision has low K^+ yield
 - » longer time during reaction for rescattering ?
 - need multi-strange measurement at AGS (E896)

K⁺/π⁺ at Mid-Rapidity in Central Au+Au



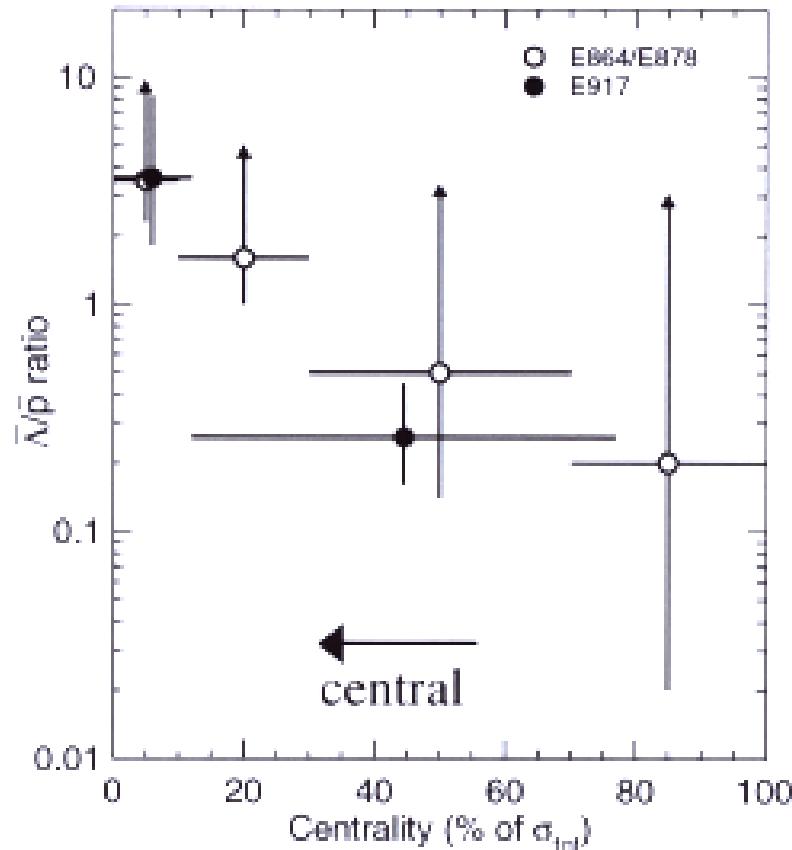
E866, E917
Phys. Lett. B
476, 1 (2000)

NA49 F.Sikler
IMSD 2000

- ◆ K⁺/π⁺ in A+A increases with E_{beam}, possible maximum
- ◆ Divide by K⁺/π⁺ (p+p) : enhancement largest at lower E_{beam}
 - enhancement smoothly decreases AGS => SPS
 - smooth evolution of reaction mechanism
- ◆ Maximum K⁺/π⁺ is convolution of rising p+p, falling enhancement

Strange Anti-baryons

- ◆ Si+Au 14.6AGeV/c (E859) $\bar{\Lambda}/\bar{p} = 2.9 \pm 0.9 \pm 0.5$
- ◆ Au+Au 10.7 AGeV (E917) $\bar{\Lambda}/\bar{p} = 3.6 \pm^{4.7}_{1.8}$



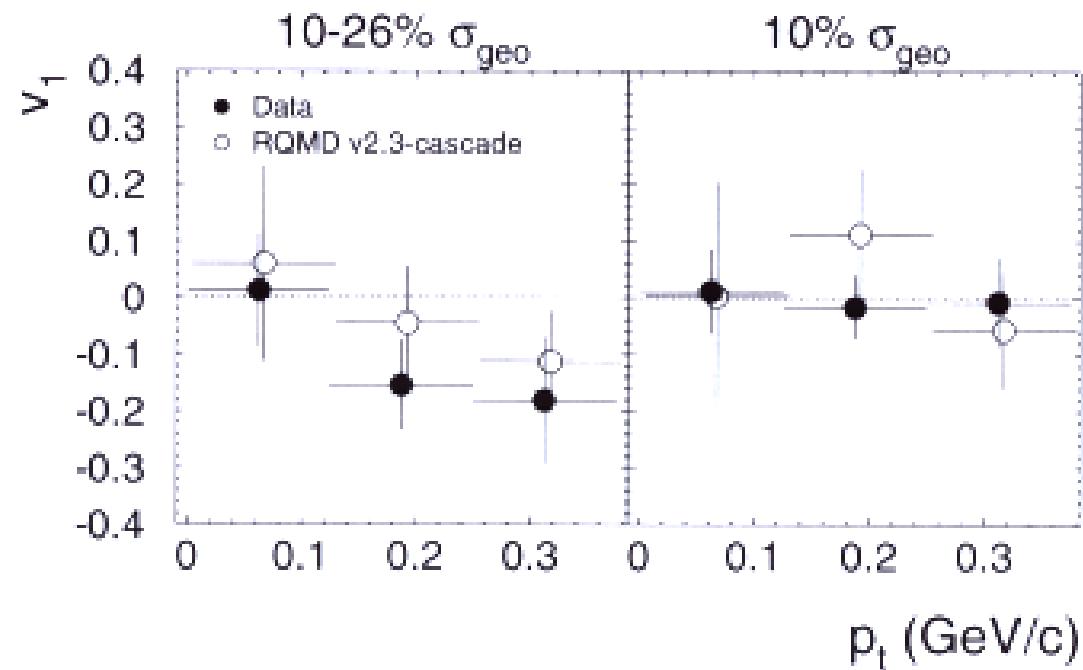
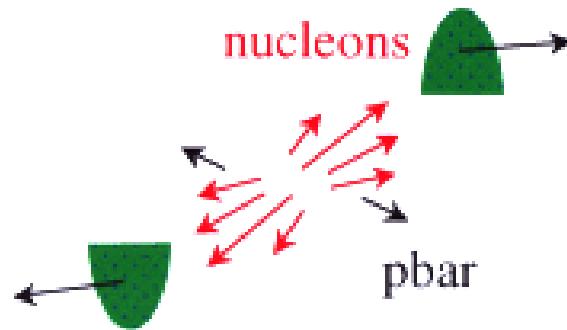
$\bar{\Lambda}/\bar{p}$ increases with centrality

UrQMD $\bar{\Lambda}/\bar{p} \sim 1.3$ (F.Wang)
Thermal $\bar{\Lambda}/\bar{p} \sim 0.9$ (J. Cleymans)

Burt Holzman E917 Talk
Saskia Mioduszewski E910
An Tai E941

E877 Anti-Flow

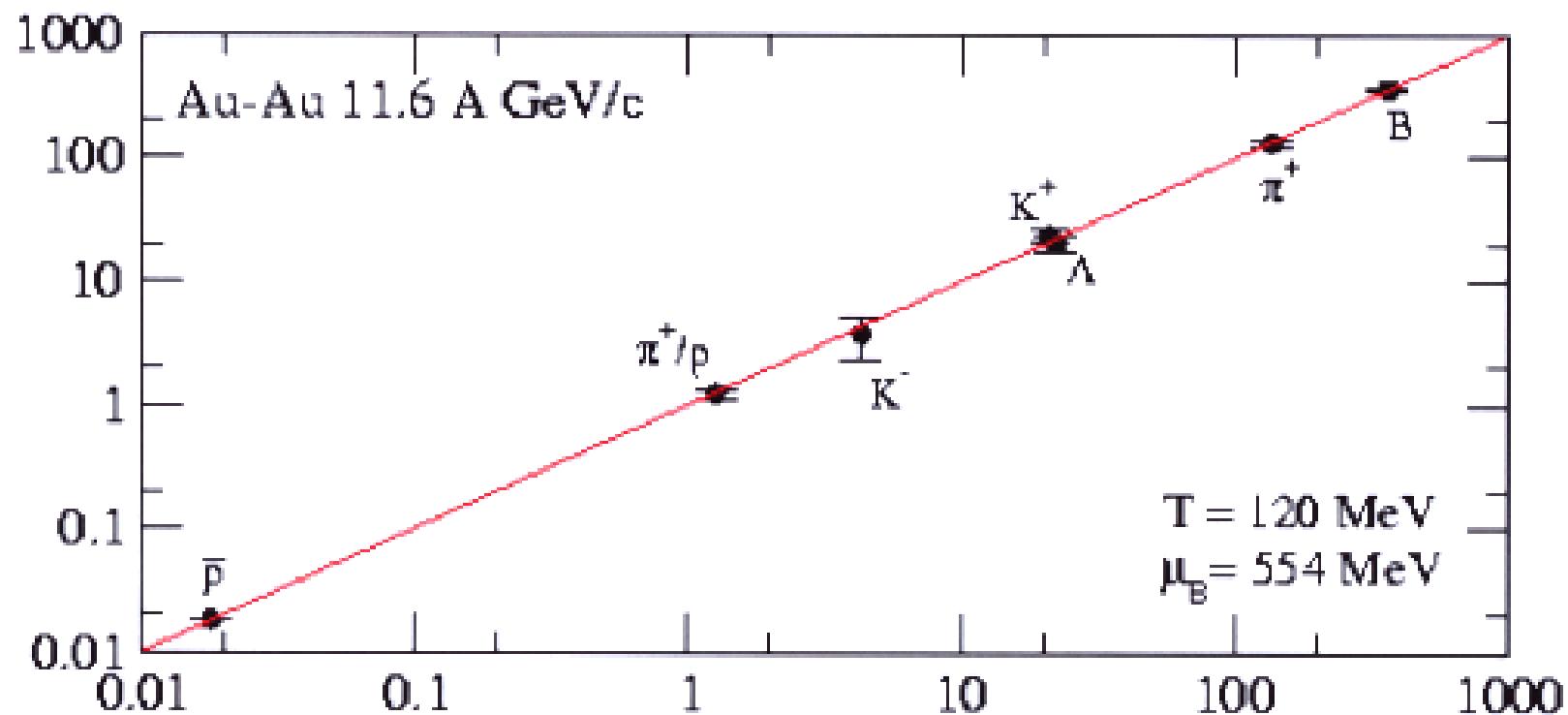
- ◆ Forward rapidity $1.8 < y < 2.2$ ($y_{nn} = 1.6$)
 - protons flow and Fourier coefficient, $v_1 > 0$
 - anti-protons are absorbed, $v_1 < 0 \Rightarrow$ constrain absorption



J. Barrette et al., Phys. Lett B485 319 (2000)

Thermal Model

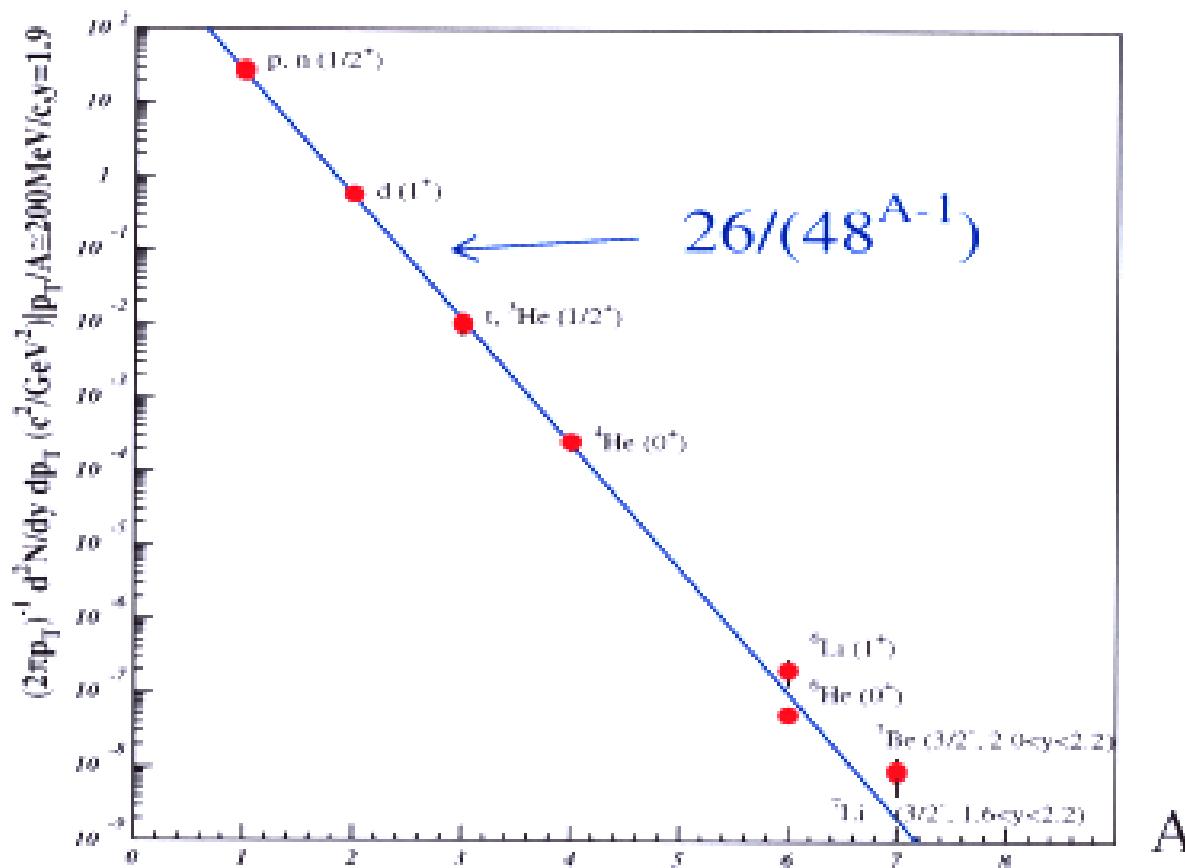
- ◆ Thermal model fits to particle yields
 - impressive agreement



Becattini et al hep-ph 0011322, hep-ph 0002267

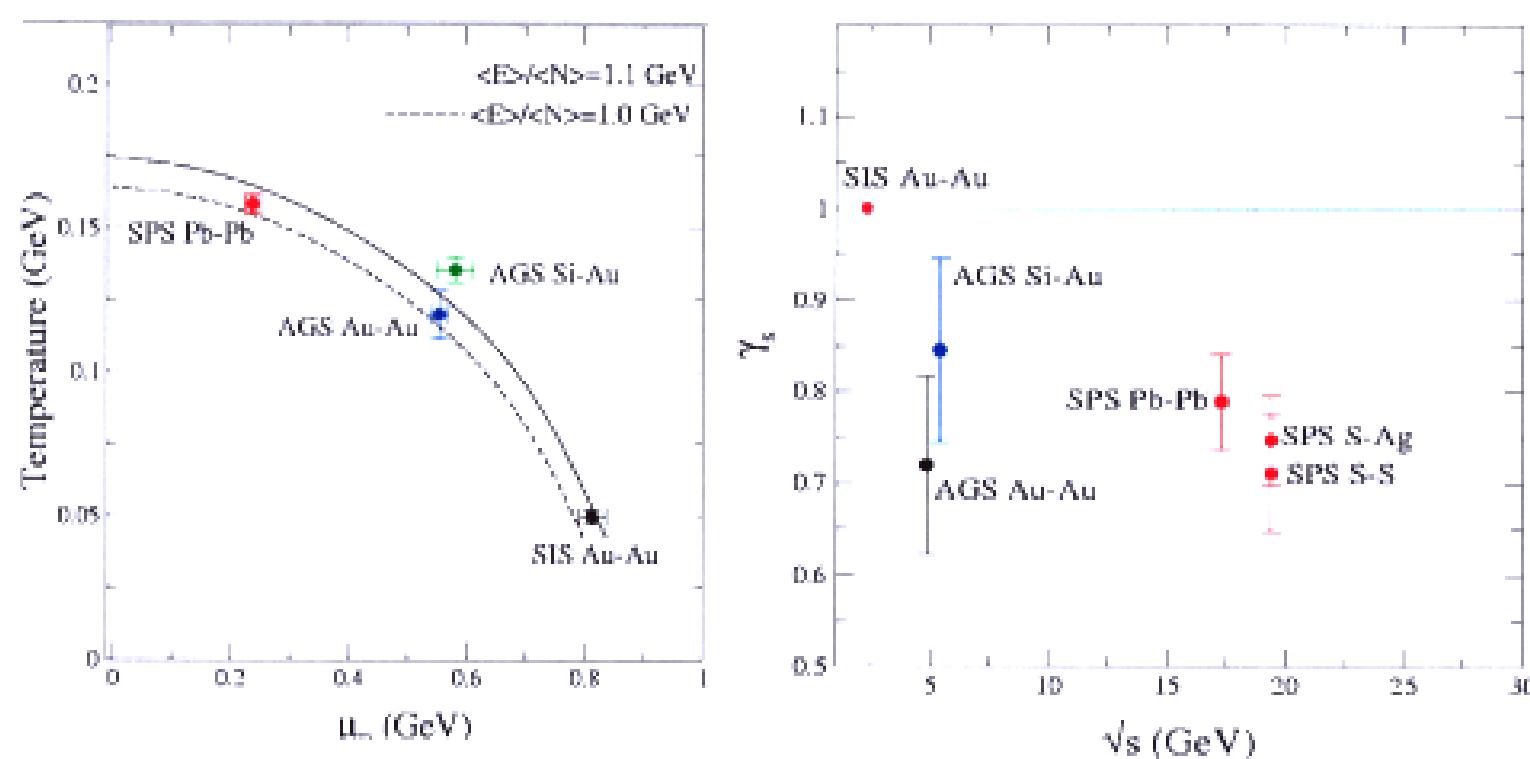
Challenge for Thermal Model

- Can model reproduce full range of measured fragments
 - are conditions at late stage different?



E864, Phys.Rev.
C61, 064908 (2000)

Thermal Fit Parameters : Strangeness Saturation γ_s

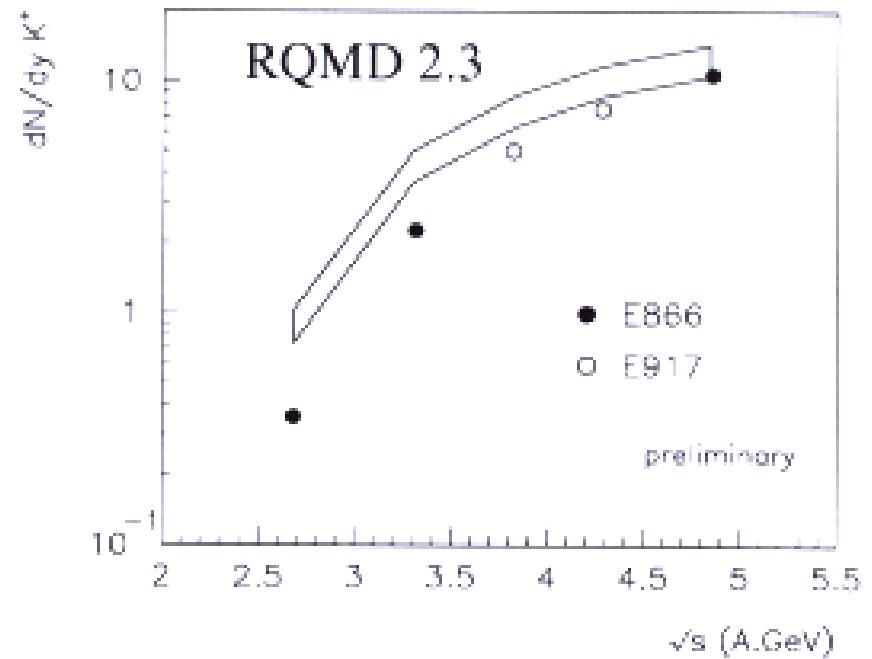
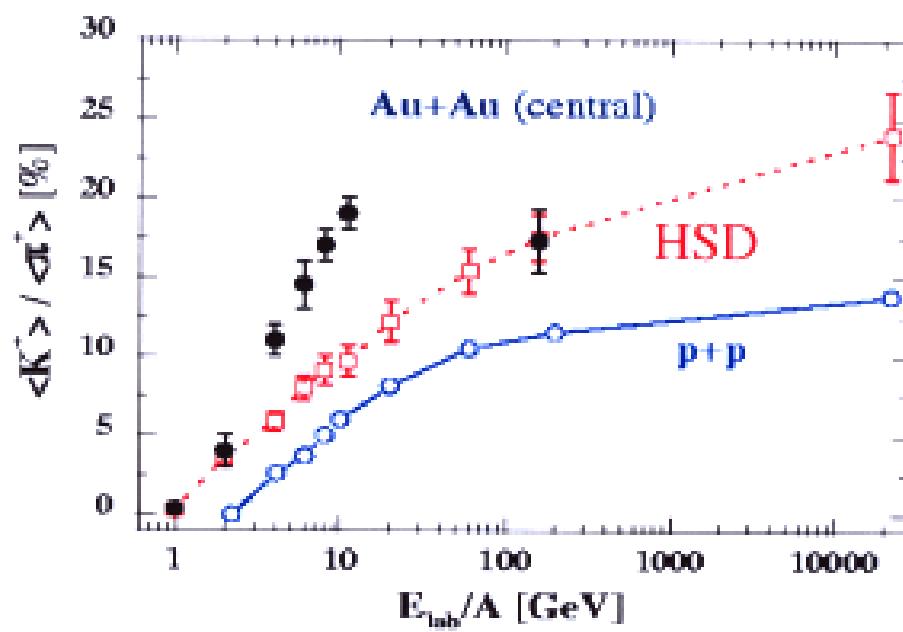


Becattini et al
hep-ph 0011322
hep-ph 0002267

- ◆ γ_s relative abundance of strange particles compared to full thermal
 - consistent with no change in γ_s between AGS and SPS
- ◆ Two theoretical conjectures
 - SPS rapid strangeness production in new state of matter => large γ_s
 - AGS rescattering of hadrons => large γ_s

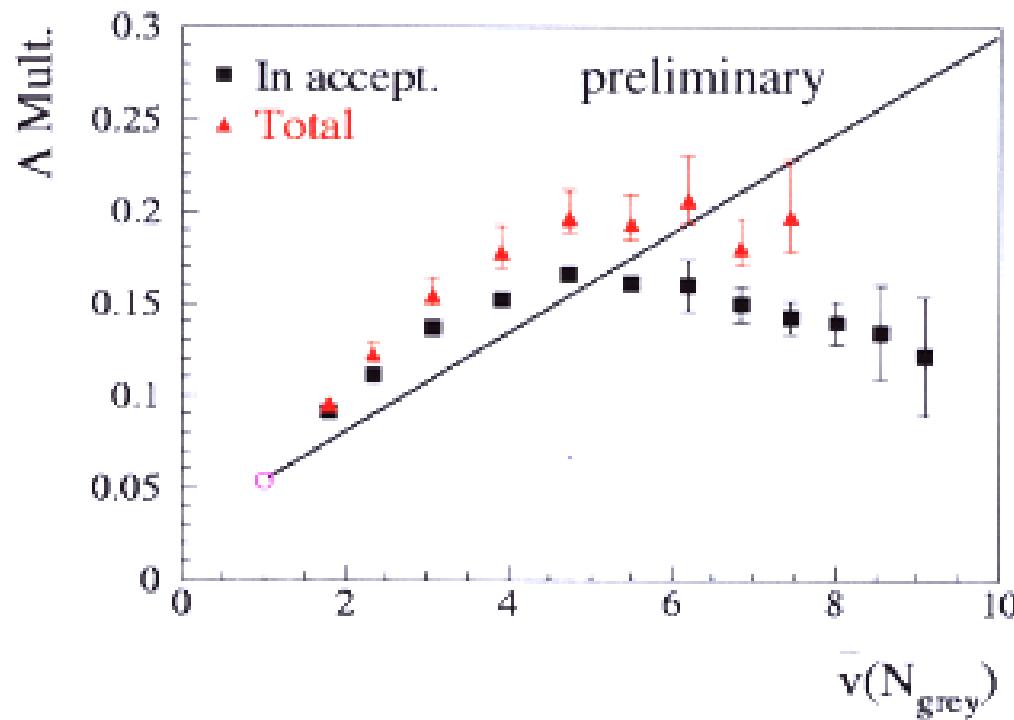
Test Conjecture of Hadronic Scattering => Large γ_s

- ◆ Do hadronic transport models reach measured strangeness ?



- ◆ HSD underpredicts data at AGS
- ◆ RQMD post-diction at 10.7 AGeV, fails other energies
- ◆ Need to understand failure of hadronic models at 1-10 AGeV/c to help interpret failure of hadronic models at 160AGeV/c

Path to Progress: p+Au 18 GeV/c, Λ Production



- ◆ Multiple collisions rapidly increase strangeness
 - Glauber model reproduces ~70% Au+Au strangeness yield (Brian Cole pA Talk)
- ◆ Λ polarization in Au+Au (Rene Bellwied E896 talk)
- ◆ Use both as benchmarks for microscopic dynamic models

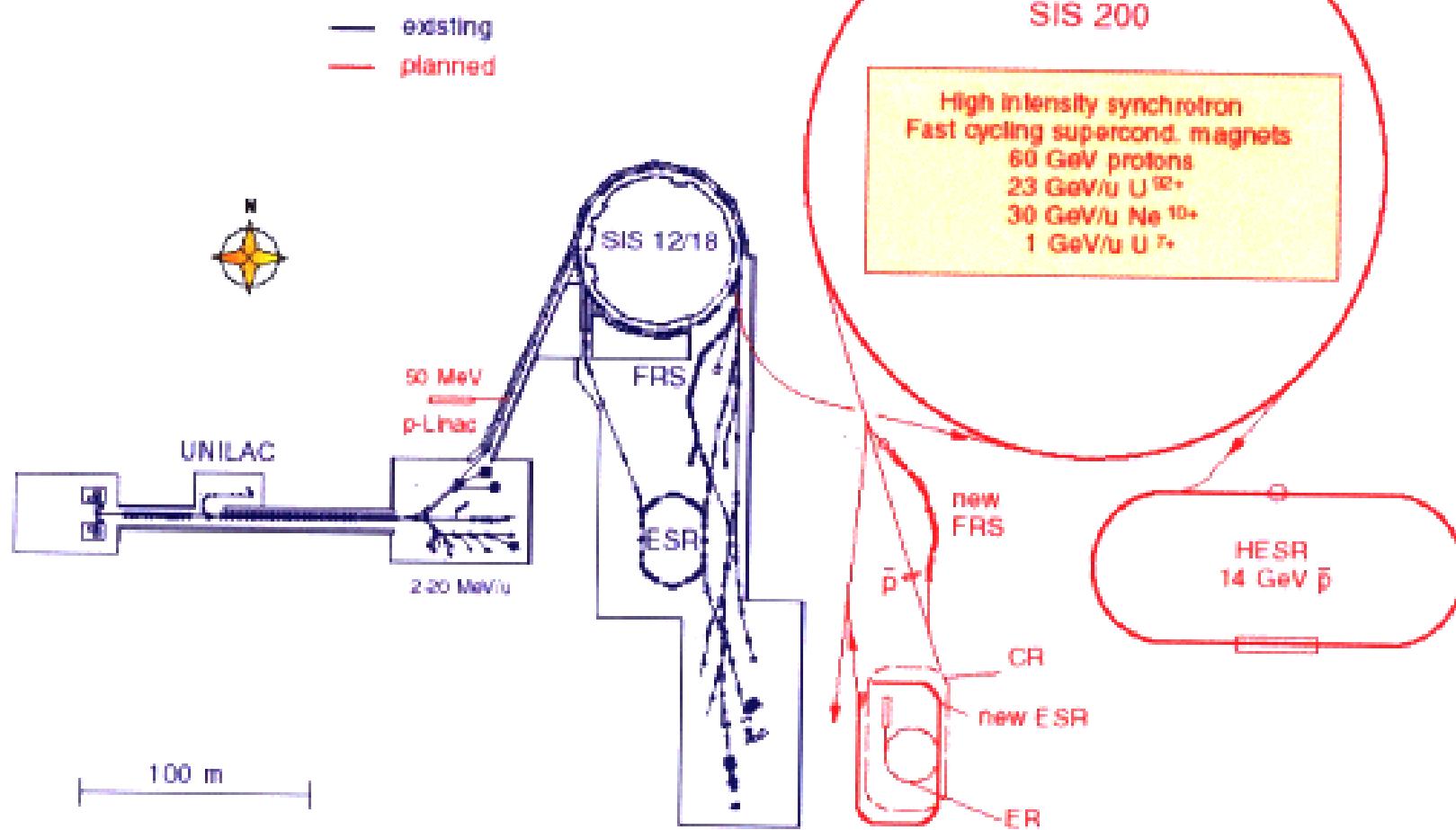
Future Opportunities In Dense Matter

- ◆ Analysis of SPS run @ 40 A GeV
- ◆ GSI upgrade 1 – 25 AGeV , up to U+U
 - properties of dense matter
 - » e^+e^-
 - » flow: directed, elliptic
 - » multi-strange, γ_s vs. E_{beam}
 - » $\bar{\Lambda}/\bar{p}$
- ◆ JHF funded for protons, heavy-ion will require additional funding
- ◆ AGS accelerator during RHIC era,
 - \$ and manpower ? for e^+e^- , multi-strange
- ◆ Feasibility of reaching color superconducting phase ?

GSI Upgrade Under Review 2001

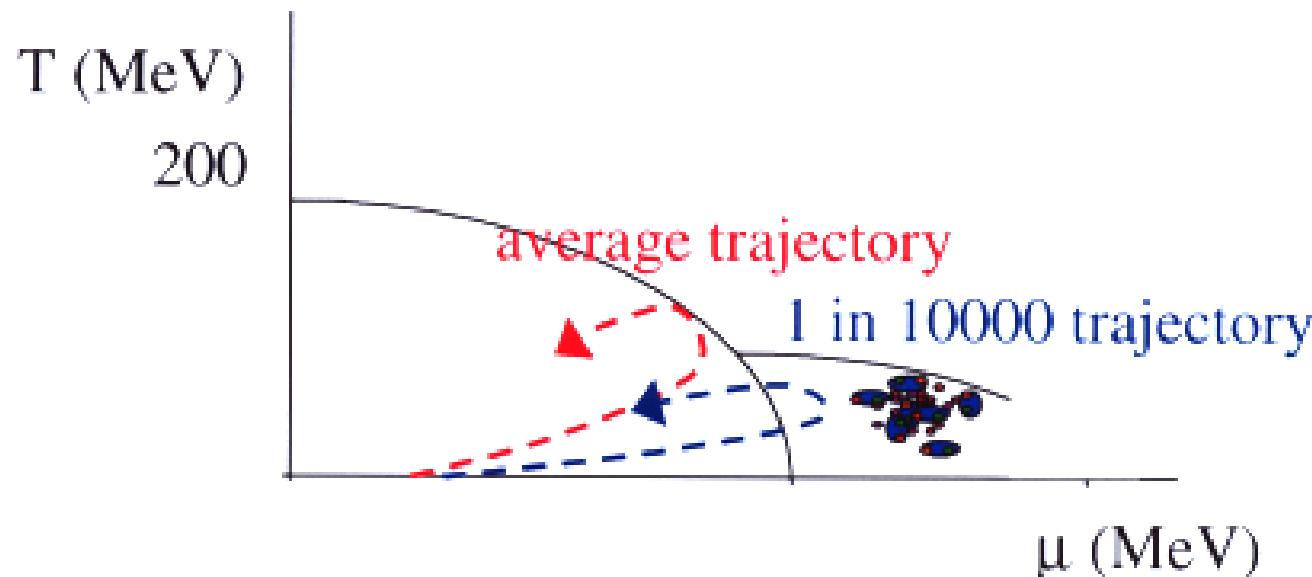


Accelerator Facilities



U+U 1-25 AGeV : Color Superconductor Phase

- ◆ $T < 50 \text{ MeV}$, several $\rho/\rho_0 \Rightarrow$ hard to access in heavy-ions
- ◆ “reaction trajectory” (caveats: non-equilibrium...)
 - what is the variation in this trajectory event-by-event ?
 - in the tail of this random variation
 - » is there a class of collisions that form dense, less excited matter? how to select these?



Conclusions: Properties of Dense Hadronic Matter

- ◆ Dynamical observables: flow, p_t spectra
 - well reproduced by incorporating many-body effects into a mean-field (density, momentum)
 - critical checks, pA x-distributions, HBT function of ϕ , ...
- ◆ Particle production
 - strangeness enhancement largest at lower E_{beam}
 - » more collisions per participant \Rightarrow more production
 - thermal model successful: strangeness $\gamma_s \sim 0.7$ AGS and SPS
 - hadronic transport models do not reproduce data
 - » use pA particle production to benchmark
- ◆ No direct evidence that baryon-rich QGP has been observed at AGS, and many observables behave similarly at AGS and SPS
- ◆ Must understand hadronic baseline before claim new state of matter at SPS